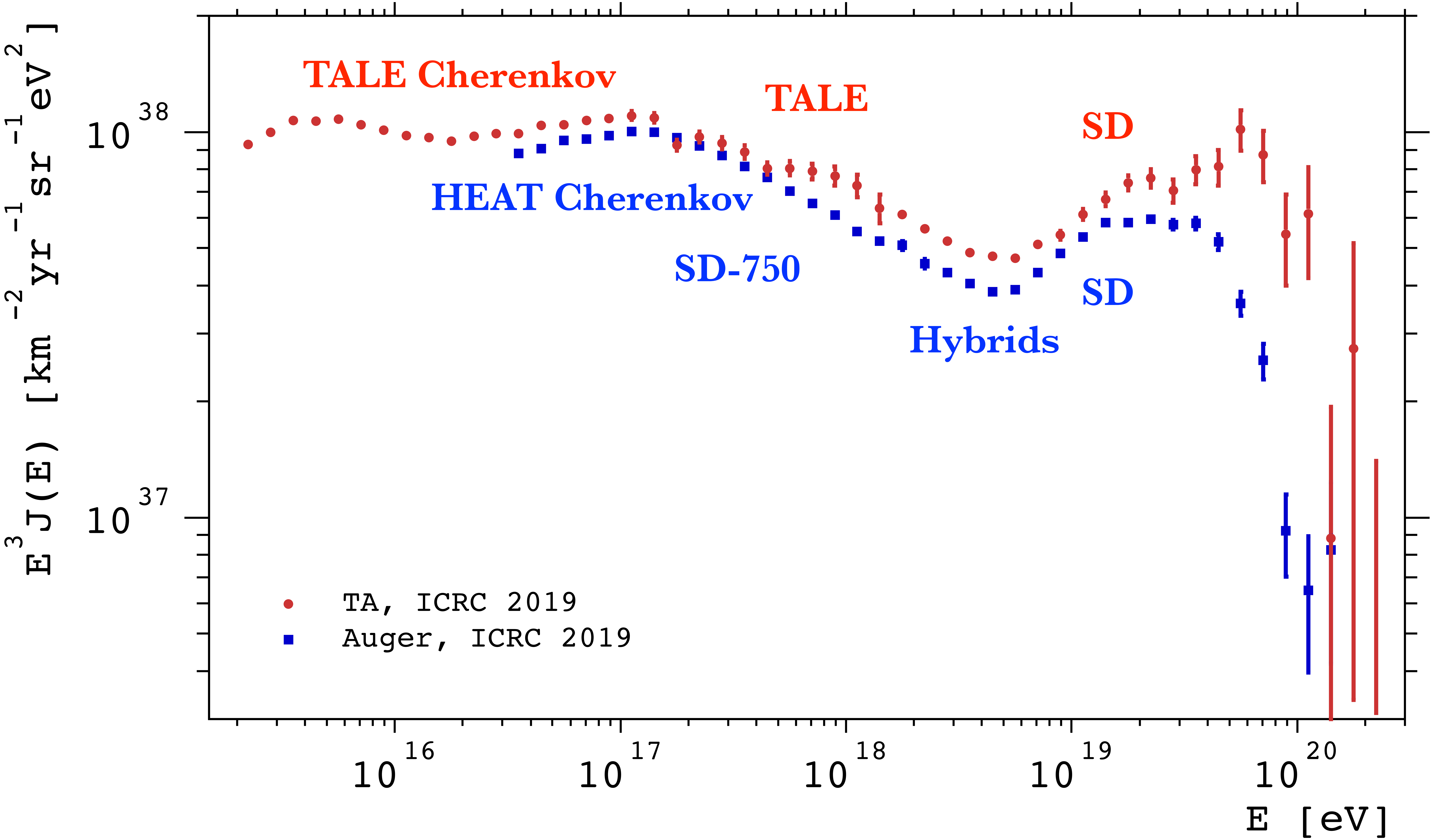
The energy spectrum of ultra-high energy cosmic rays measured at the Pierre Auger Observatory and at the Telescope Array

Tareq AbuZayyad, **Olivier Deligny,** Daisuke Ikeda, Dmitri Ivanov, Isabelle Lhenry-Yvon, Ioana Mariş, Daniela Mockler, Toshiyuki Nonaka, Markus Roth, Francesco Salamida, Gordon Thomson, Yoshiki Tsunesada, Inés Valiño, Valerio Verzi
for the Pierre Auger and Telescope Array Collaborations

ICRC #234

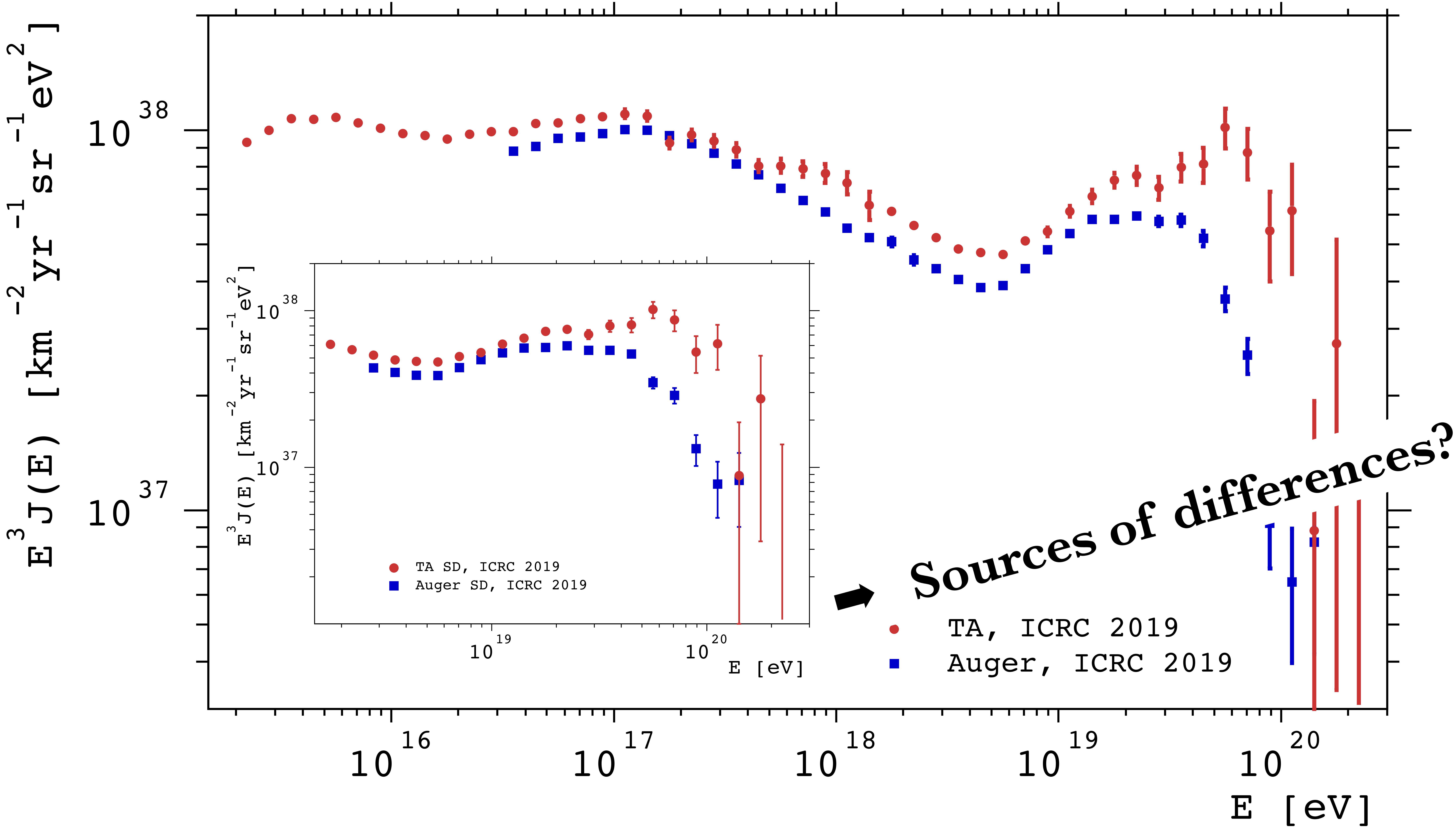
Auger/TA energy spectra at this conference



Hybrid detectors to measure spectra at UHE:

from shower sizes $S(r_{opt})$ to energies

Auger/TA energy spectra at this conference



2. Lessons from previous comparisons

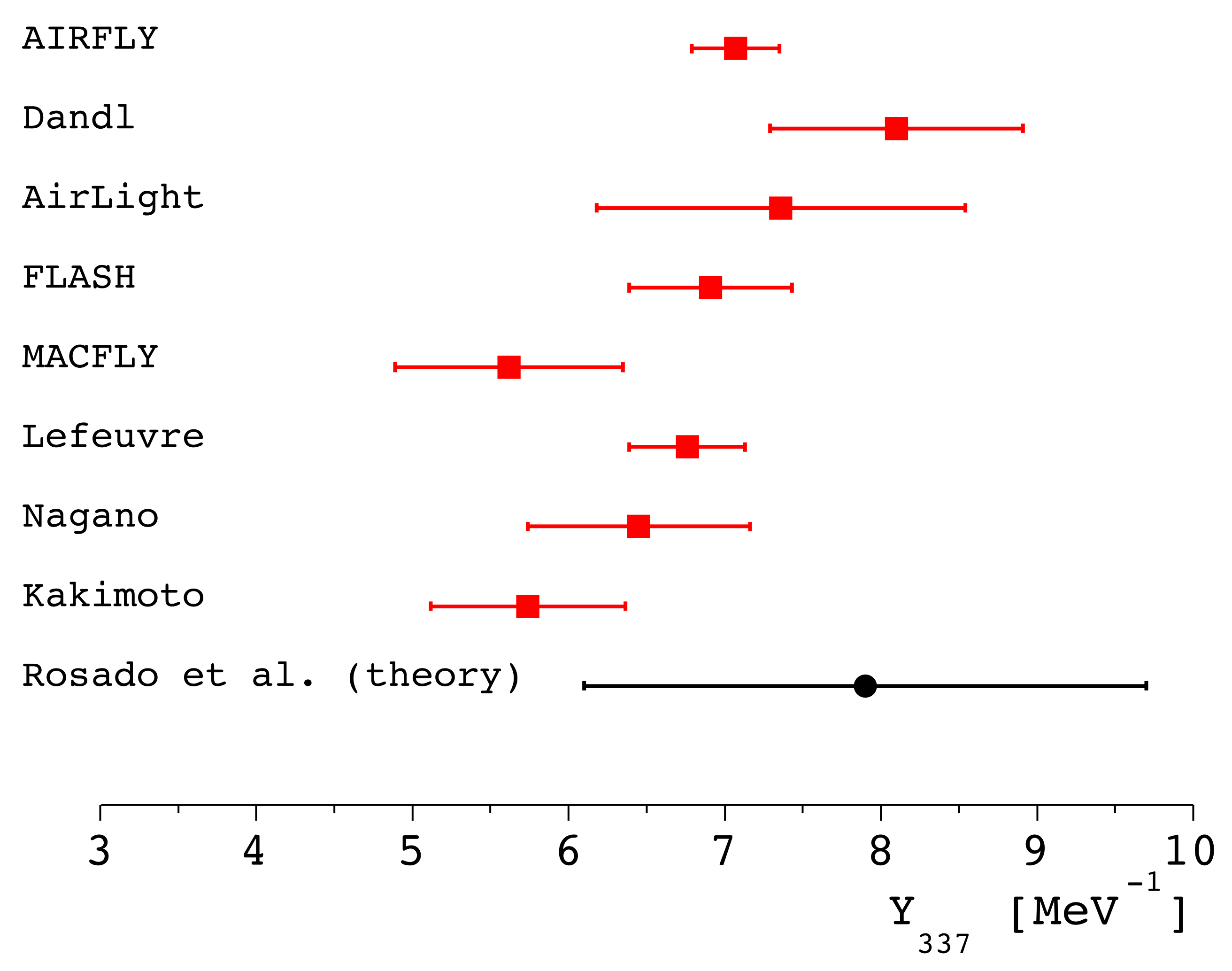
- Rescaling factor and fluorescence yield/invisible energy systematic uncertainties
- Energy-dependent rescaling factor above 10 EeV inferred in the overlapping f.o.v.
- Comprehensive search for energy-dependent systematic uncertainties

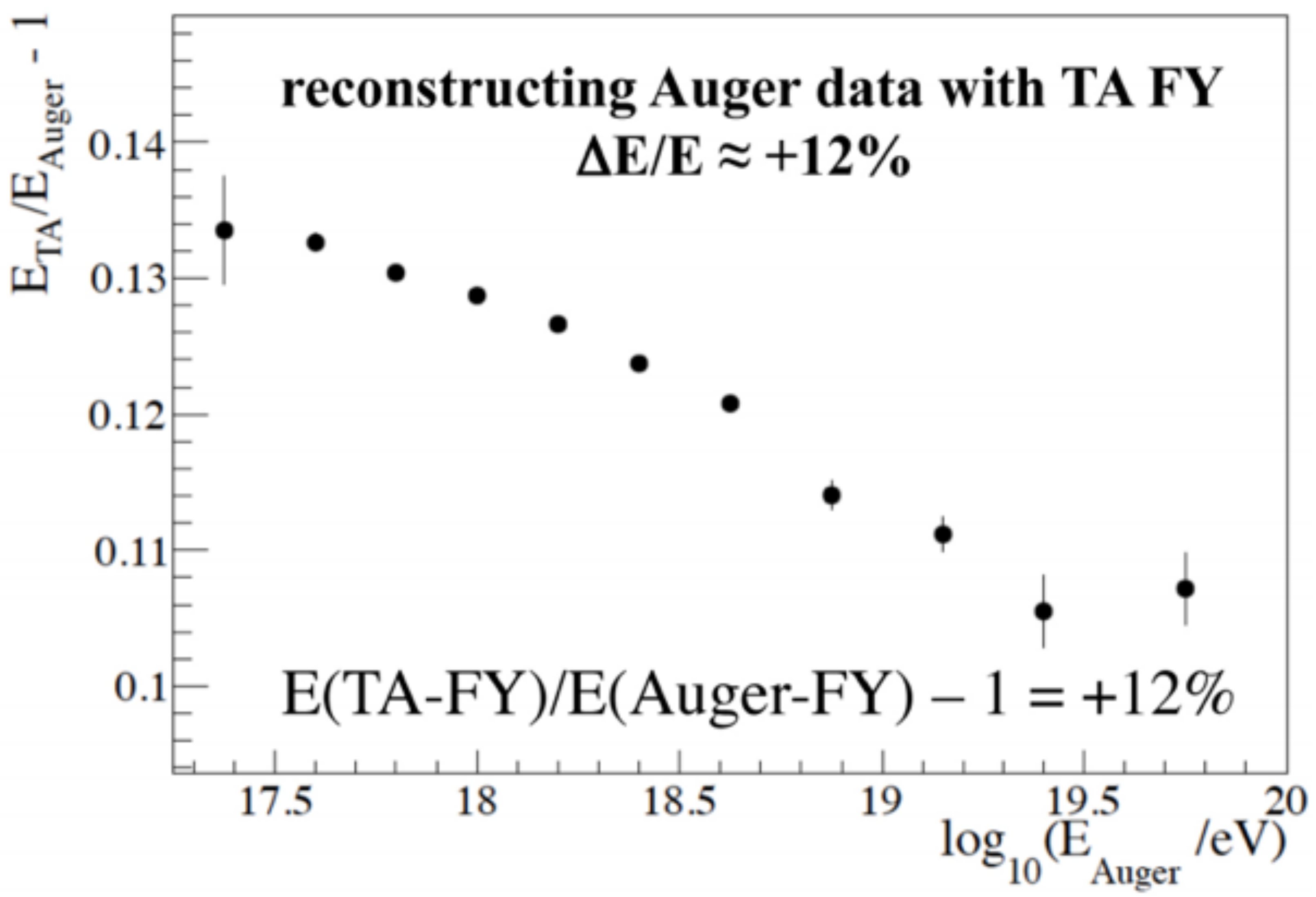
TA/Auger energy spectrum working group: a 10-year endeavor

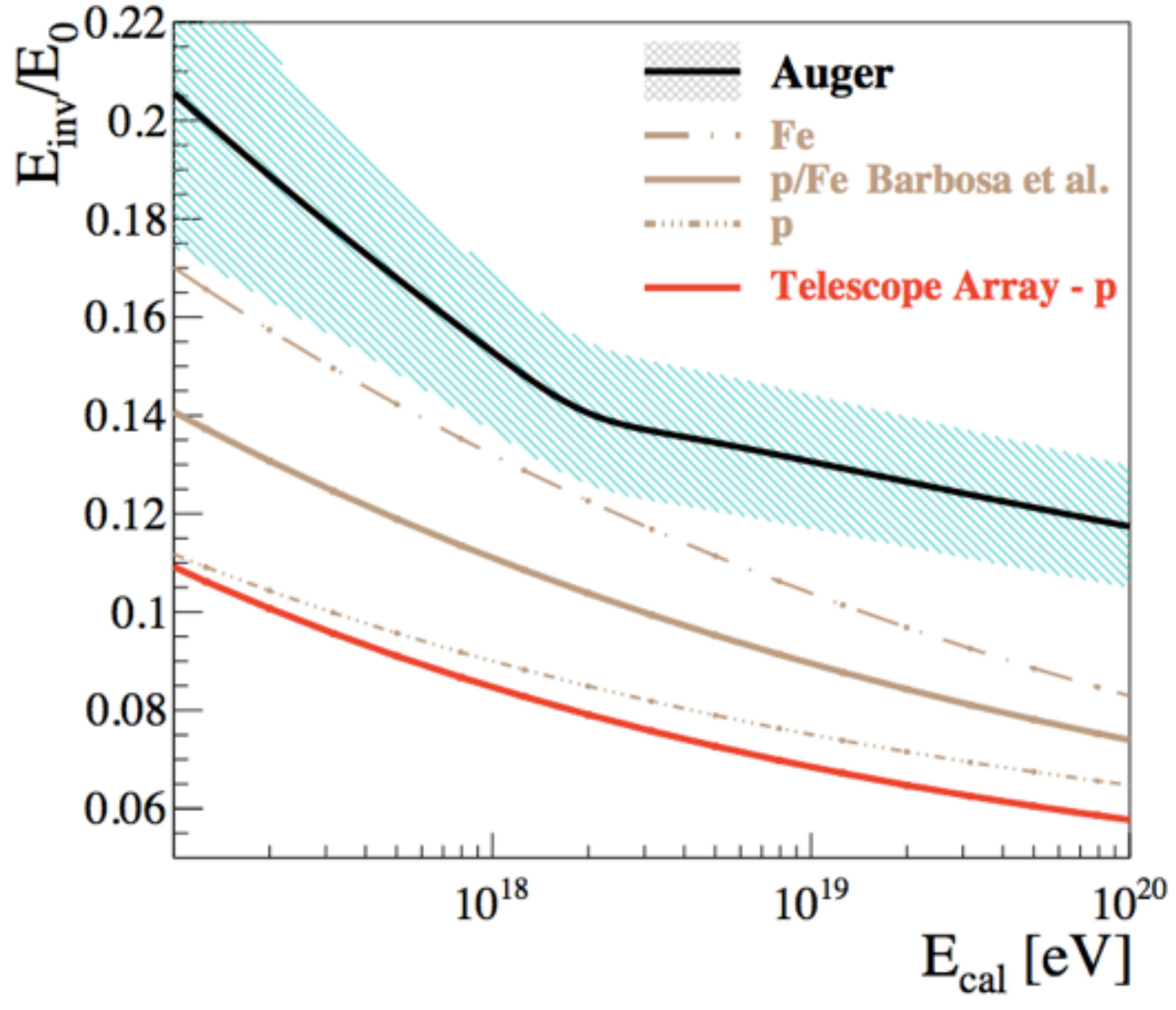
1. **UHECR2010, Nagoya, Japan —** Working group formed, aimed at comparing and cross-checking the energy spectrum results
2. **UHECR2012, Geneva, CERN —** Comprehensive review of all the ingredients to build Auger and TA spectra
3. **UHECR2014, Springdale, UT, USA —** Detailed discussion of the energy scale systematic uncertainties; First discussions on searching for spectrum-declination dependence
4. **UHECR2016, Kyoto, Japan —** Comparison of TA and Auger energy spectra in the overlapping field of view
5. **ICRC2017, Busan, Korea —** More systematic comparisons of Auger and TA spectra in the overlapping field of view using refined methods
6. **UHECR2018, Paris, France —** Comprehensive review of TA and Auger spectrum calculations using different techniques aimed at understanding the differences between Auger and TA in the common declination band

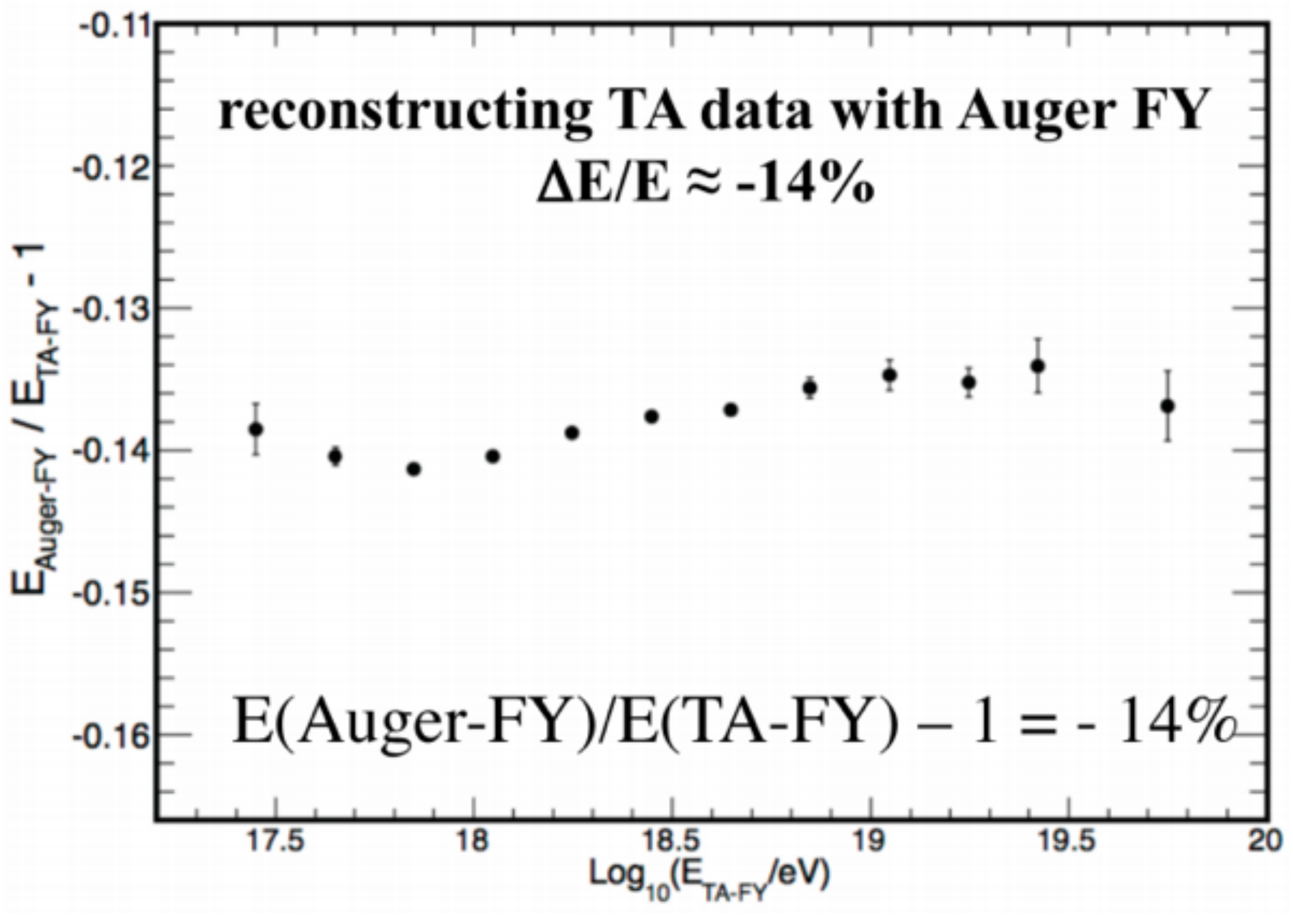
- **This contribution —** Extension of the comparisons down to 30 PeV, covering the 2nd knee, the ankle and the suppression region; Declination dependence studies

Systematic uncertainties in the absolute energy scale





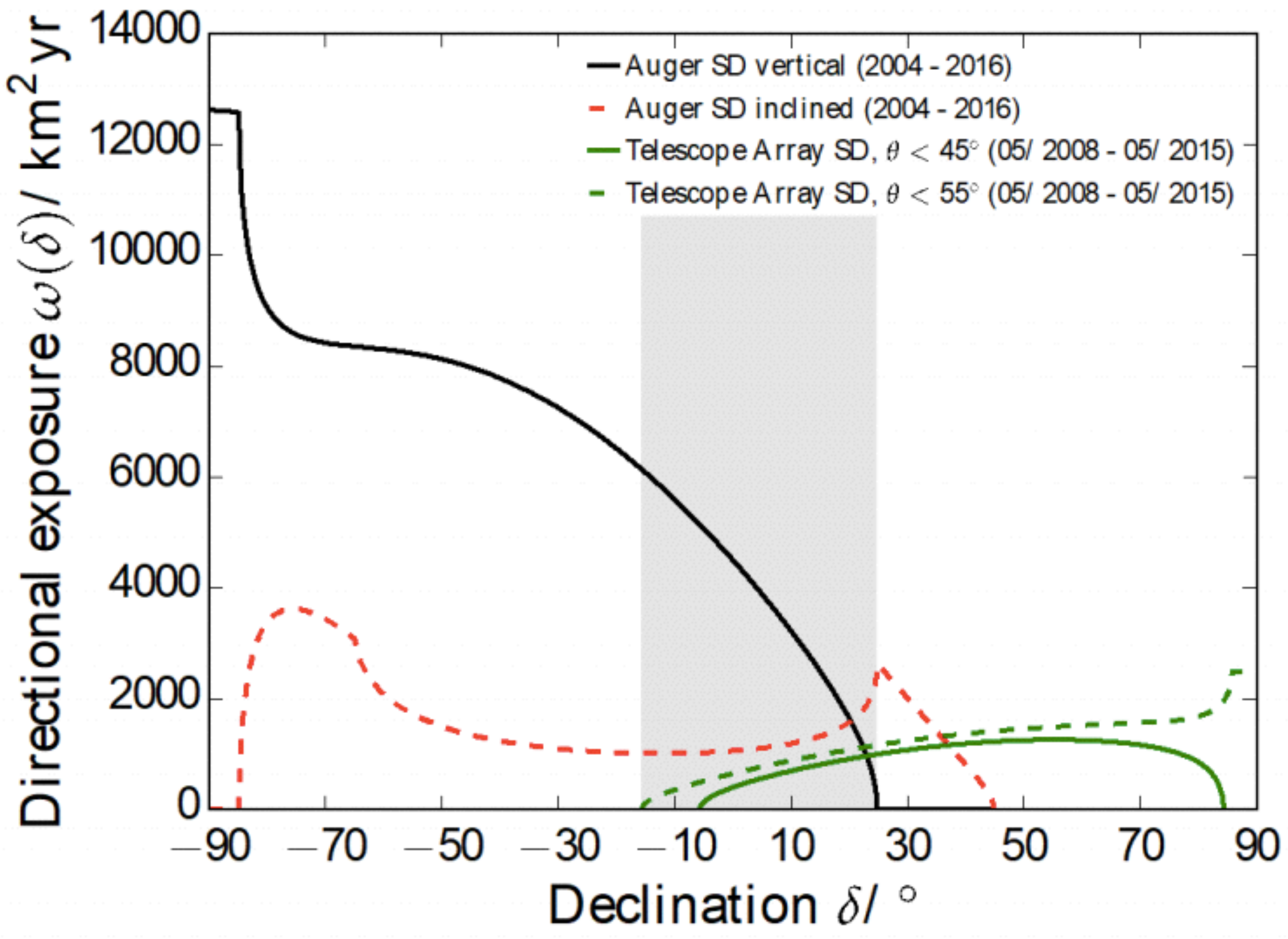




- ~10% rescaling needed to bring spectra in agreement from the ankle energy to ~10 EeV
- 10%: within energy scale systematic uncertainties (21% for TA, 14% for Auger)
- Energy dependence of the shift: smaller than 1% above 10 EeV

The common declination band

North/South anisotropies as the sources of the differences?



Taking advantage of the overlapping declination band

➡ Underlying intensity identical

➡ Energy spectra should be identical once defined as

$$J_{1/\omega}(E) = \frac{1}{\Delta\Omega\Delta E}\sum_{i=1}^{N}\frac{1}{\omega(\mathbf{n}_i)}$$

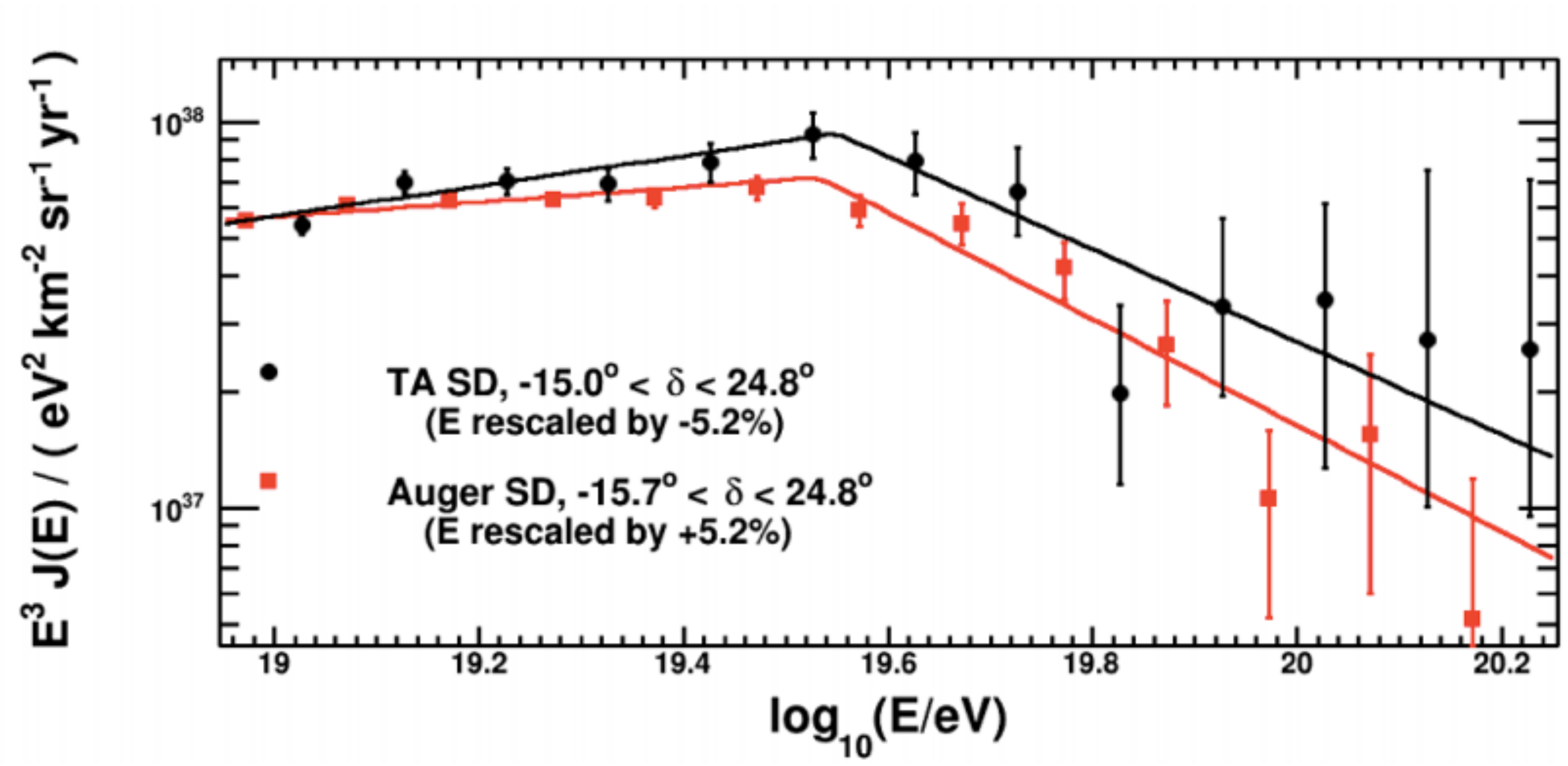
(removal of directional-exposure distortions of the spectrum induced by possible anisotropies)

$$J_{\mathrm{std}}(E) = \frac{1}{\Omega}\frac{\mathrm{d}N}{\mathrm{d}E} = J_0(E) + \frac{1}{\Omega}\int \mathrm{d}\mathbf{n}\ \omega(\mathbf{n})J_{\mathrm{anis}}(\mathbf{n},E)$$

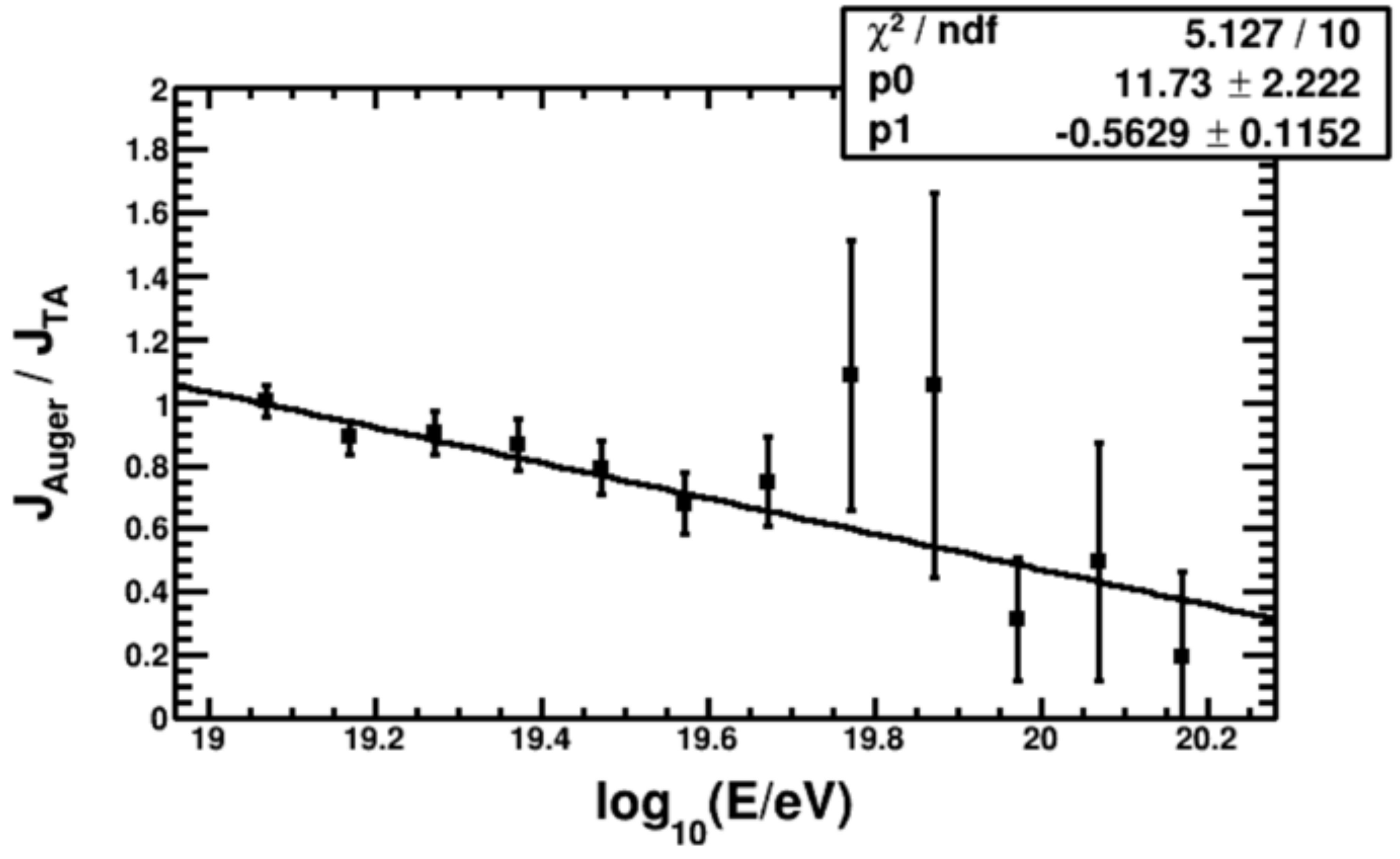
while $$J_{1/\omega}(E) \equiv \langle J(\mathbf{n},E)\rangle_{\Delta\Omega} = \frac{1}{\Delta\Omega}\int_{\Delta\Omega}\frac{\mathrm{d}\mathbf{n}}{\omega(\mathbf{n})}\frac{\mathrm{d}^2N}{\mathrm{d}\mathbf{n}\,\mathrm{d}E}$$

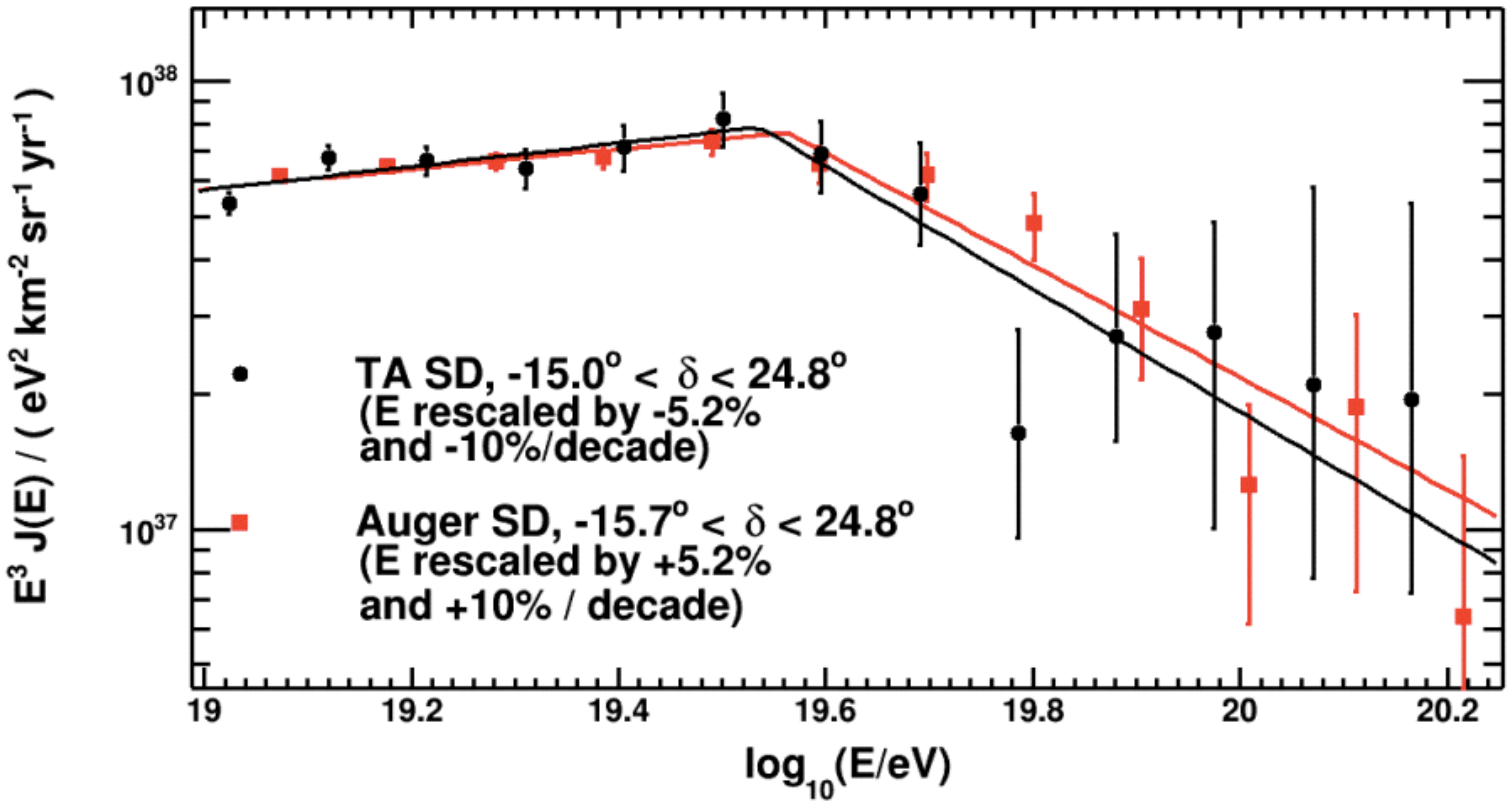
Lessons from the common declination band

[D. Ivanov et al., Proc. of UHECR 2018]



- Better agreement than whole f.o.v. spectra for the suppression energy
- Still, constant rescaling of energies insufficient to get satisfactory agreement
- Non-linearity of ~+(-)10% / decade on top of a +(-)5.2% global rescaling





±10% / decade above 10 EeV?

Comprehensive search for energy-dependent systematics

EPJ Web of Conferences **210**, 01002 (2019) https://doi.org/10.1051/epjconf/201921001002
UHECR 2018

[D. Ivanov et al., Proc. of UHECR 2018]

Auger-TA energy spectrum working group report

Tareq AbuZayyad[1], *Olivier* Deligny[2], *Daisuke* Ikeda[3], *Dmitri* Ivanov[1], *Isabelle* Lhenry-Yvon[2], *Ioana* Mariş[4], *Daniela* Mockler[8], *Toshiyuki* Nonaka[3], *Markus* Roth[5], *Francesco* Salamida[6,7], *Gordon* Thomson[1], *Yoshiki* Tsunesada[9], *Inés* Valiño[10,11], and *Valerio* Verzi[12], for the Pierre Auger[13] and Telescope Array[14] Collaborations

- Energy uncertainties due to aerosols
- Invisible energy corrections
- FD fluorescence yield
- Energy calibration uncertainties
- Checks with constant intensity cut
- Checks with hybrids

TA

Source of nonlinearity	Amount (% per decade)
FD Invisible energy	1% ± 1%
FD Fluorescence yield	−1% ± 1%
FD Aerosols	1.7% ± 1%
SD and FD comparison	−2% ± 9%
Net	−0.3% ± 9%

Auger

Source of nonlinearity	Amount (% per decade)
Aerosols	±1%
Calibration	±1%
SD and FD comparison	±2%
Constant Intensity Cut	±2%
Net	±3%

➡ Some possible non-zero non-linearity, but much smaller than ±10% / decade

±10% / decade above 10 EeV?

Comprehensive search for energy-dependent systematics

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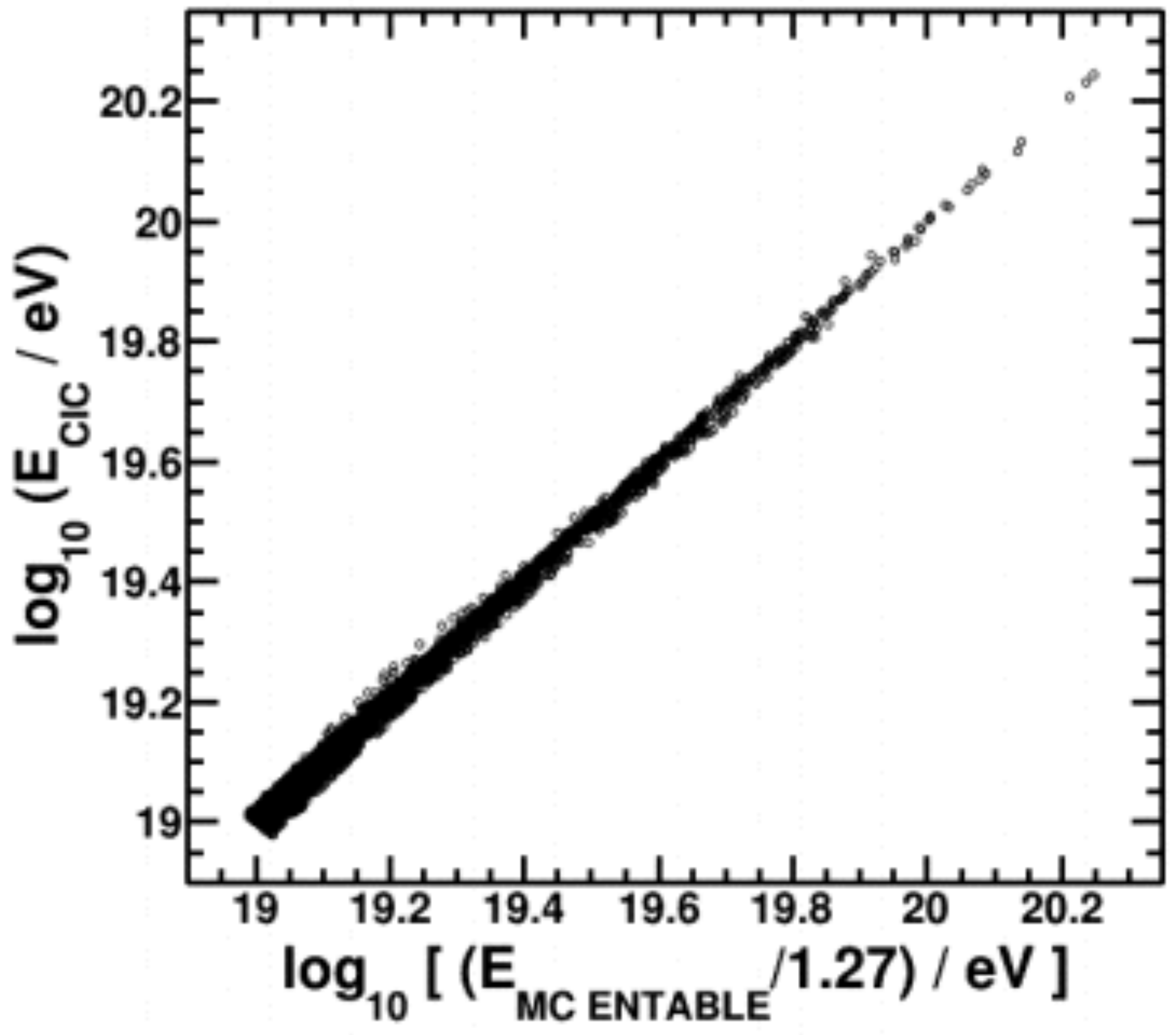
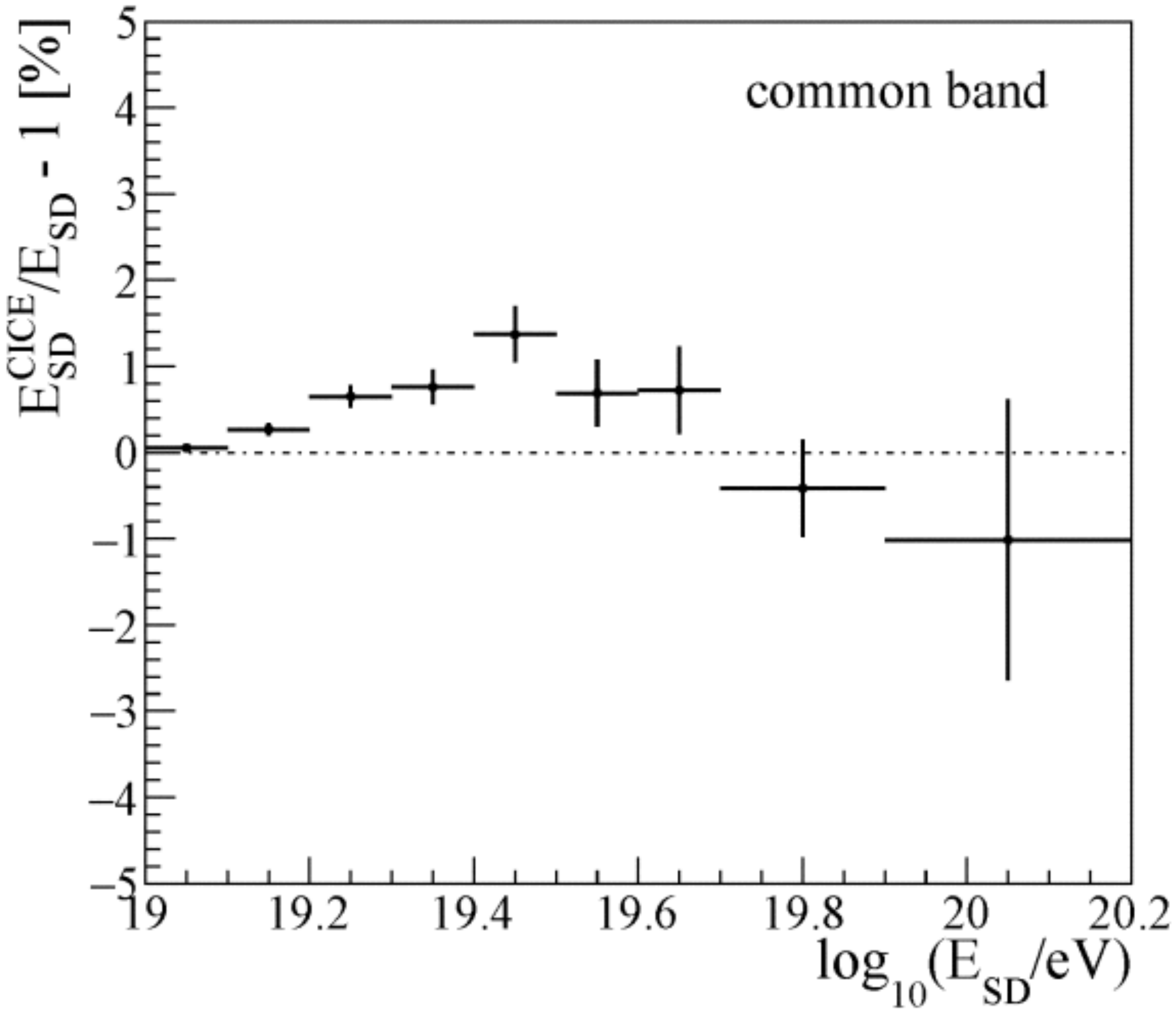
- Energy uncertainties due to aerosols
- Invisible energy corrections
- FD fluorescence yield
- Energy calibration uncertainties
- Checks with constant intensity cut
- Checks with hybrids

Comprehensive search for energy-dependent systematics — Constant Intensity Cut

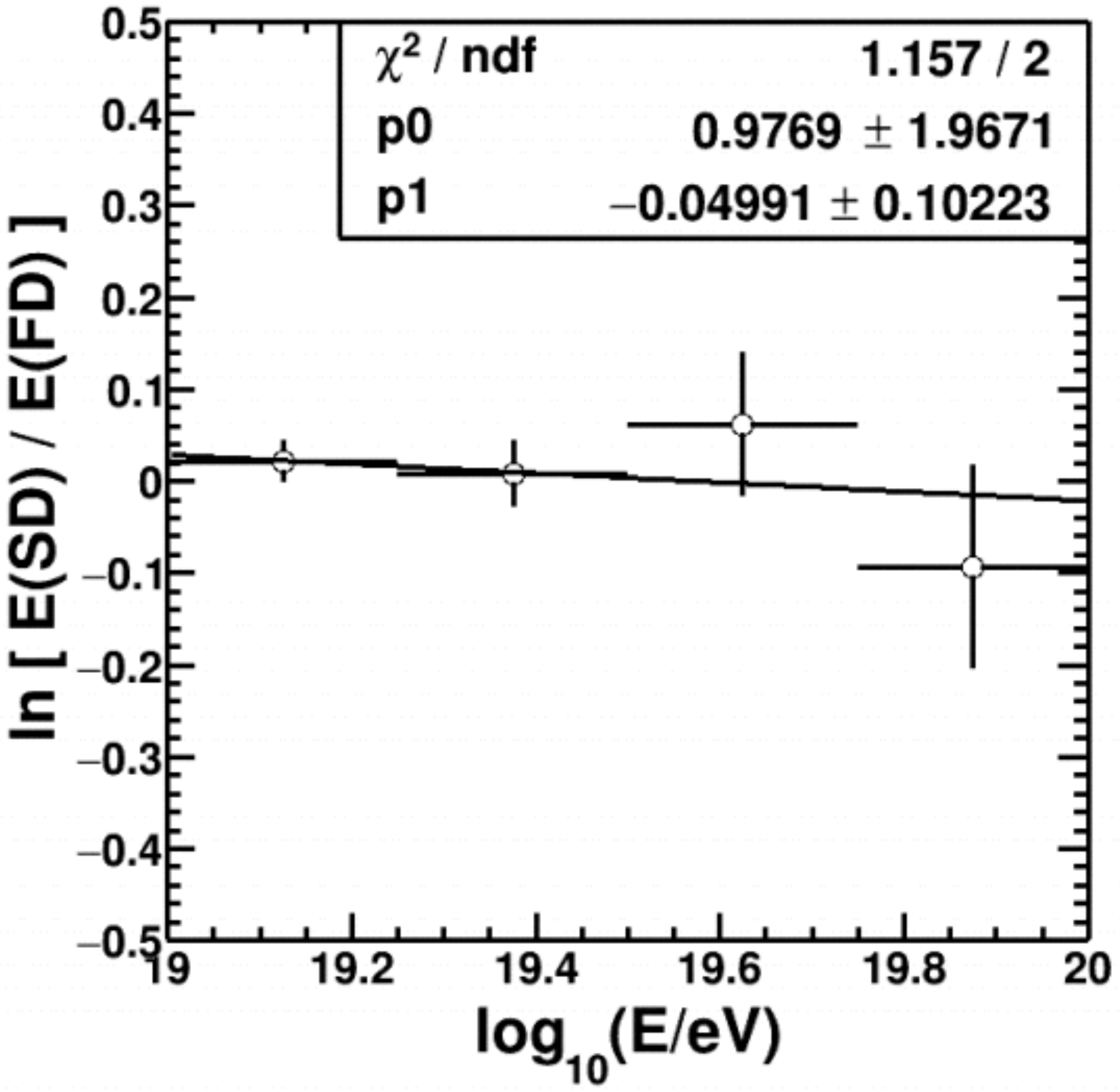
- TA: Compare TA Constant Intensity Cut and TA original MC based energy reconstruction methods

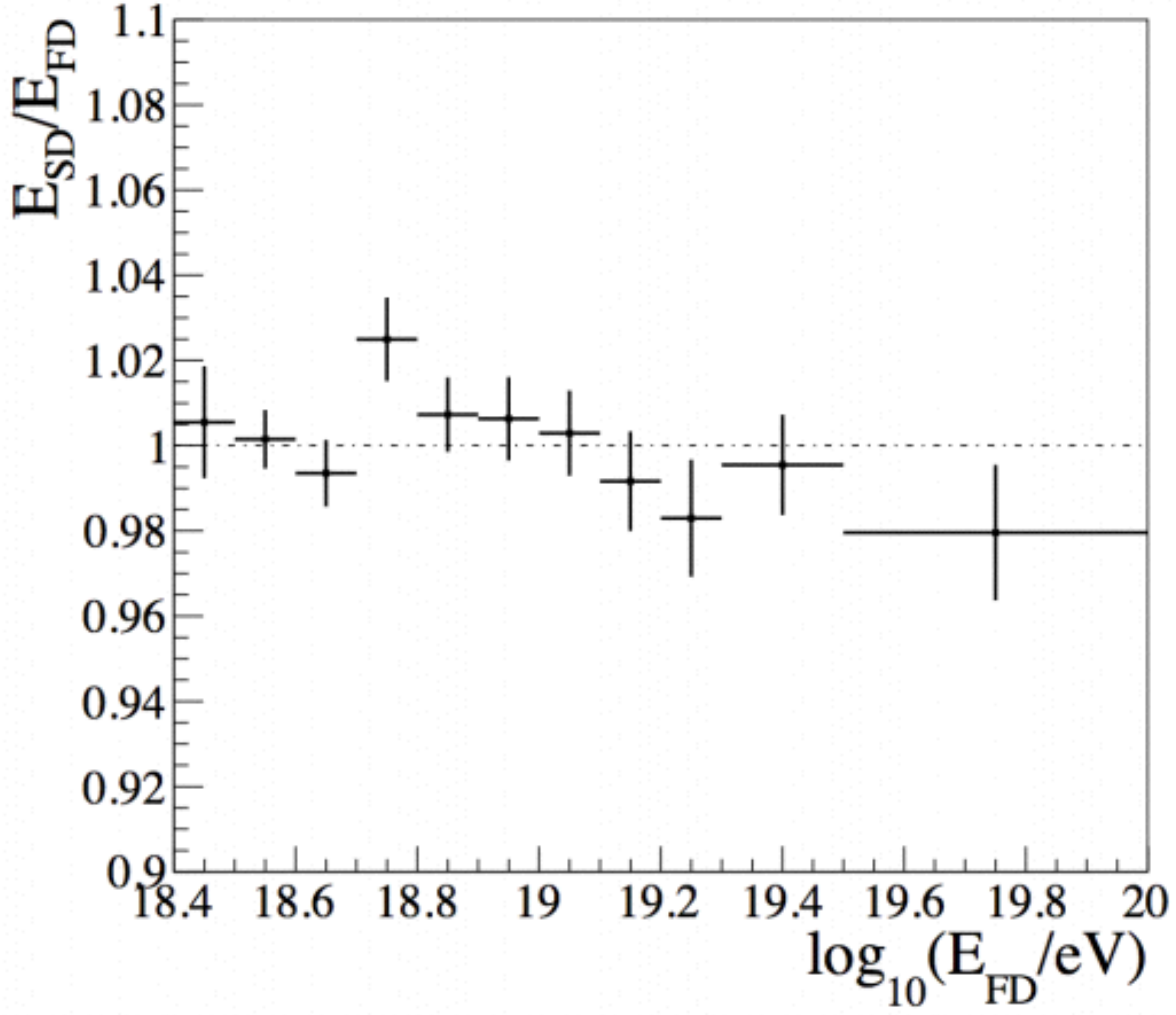


- Auger: CIC vs energy-dependent CIC



Comprehensive search for energy-dependent systematics — Checks with hybrids

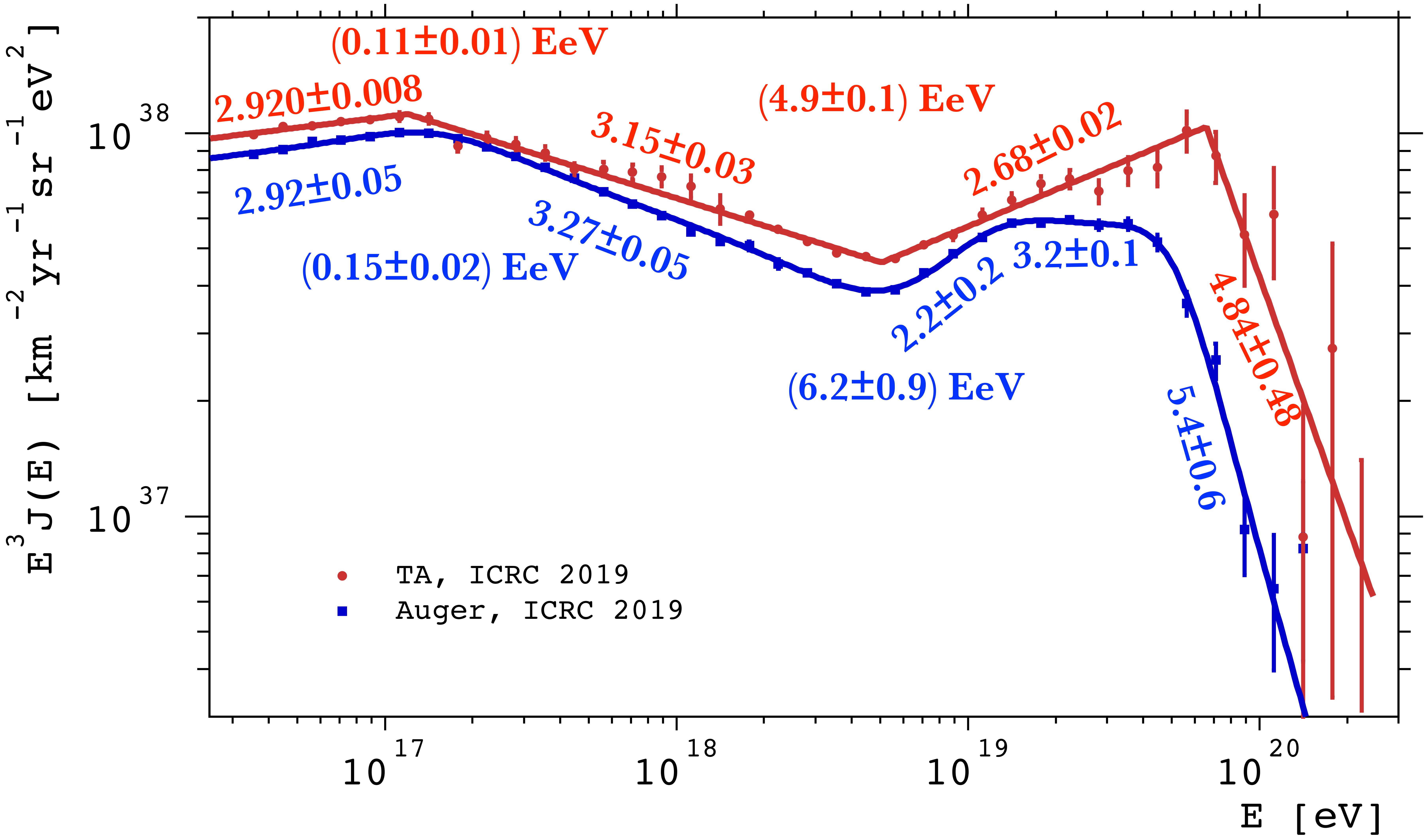




3. Energy scale differences inferred from the fitted differential spectra

- The approach
- Rescaling factors from the second knee to the ankle
- Rescaling factors in the energy range of the suppression

Spectral features



Low energy comparisons:

- γ_0: agreement!
- 2nd knee position: within 1.8σ
- γ_1: within 2.1σ

- Energy scale: different invisible energy corrections in that range (with some energy dependence)
- More comprehensive studies needed (with other experiments as well)

Deriving the energy shifts from the fitted *differential* spectra

➡ Making use of the *differential* fitted functions to calculate in a single step the energy-dependent rescaling factor $b(E)$ needed to get consistent spectra

- Hypothesis 1: TA spectrum right, Auger one biased due to $b(E)$ bias in E
- Hypothesis 2: Auger spectrum right, TA one biased due to $b(E)$ bias in E

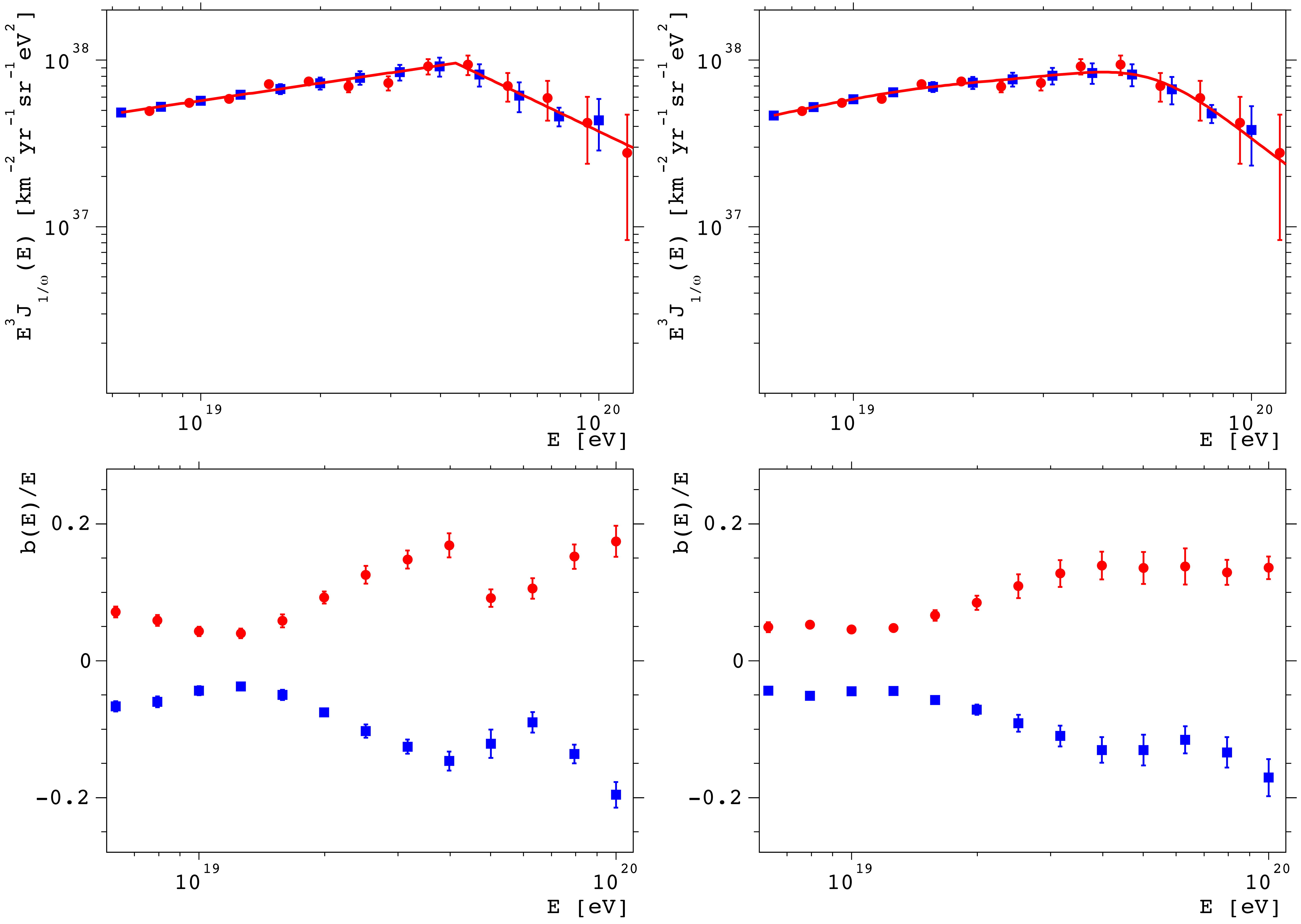
- $b(E)$ defined by $J_x(E+b(E)) = J_y(E)$ — Test single vs double broken power law suppression function

➡ Numerical solving of the truncated Taylor expansion

$$J_X(E) - J_Y(E) + \sum_{k=1}^{k=N} \frac{b(E)^k}{k!} \frac{d^k J_X(E)}{dE^k} = 0$$

- Propagate variance/covariance matrix of the fitting functions to get uncertainties on $b(E)$

Non-linearity above 10 EeV in the common band



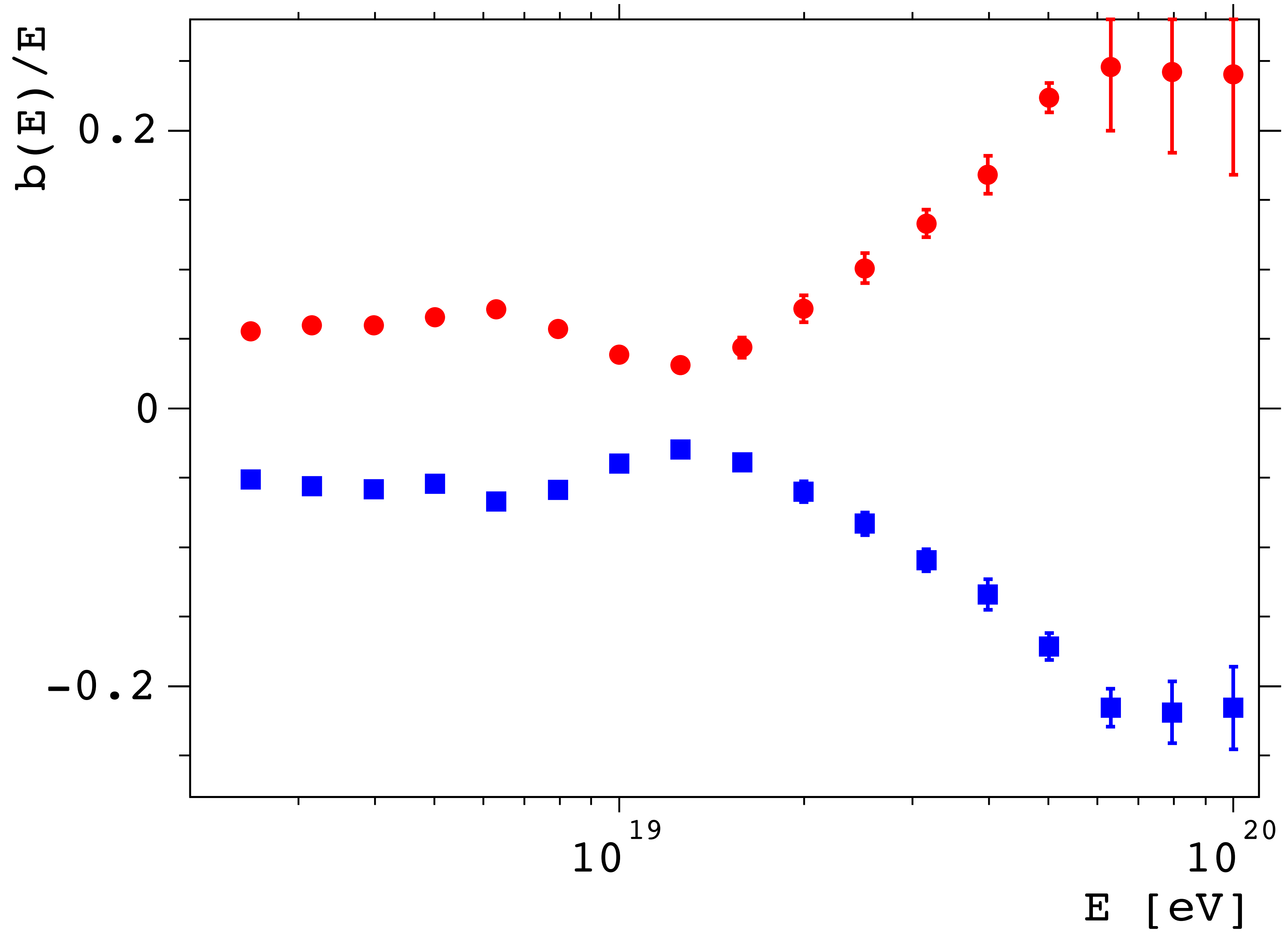
$b(E)$ in agreement with a single non-linearity (constant Auger rescaling of ~11% up to ~10 EeV, and ~20% in the [10-100] EeV decade obtained with the **integrated** spectra) obtained with the double broken power law fitting function

NB: correlations between bins

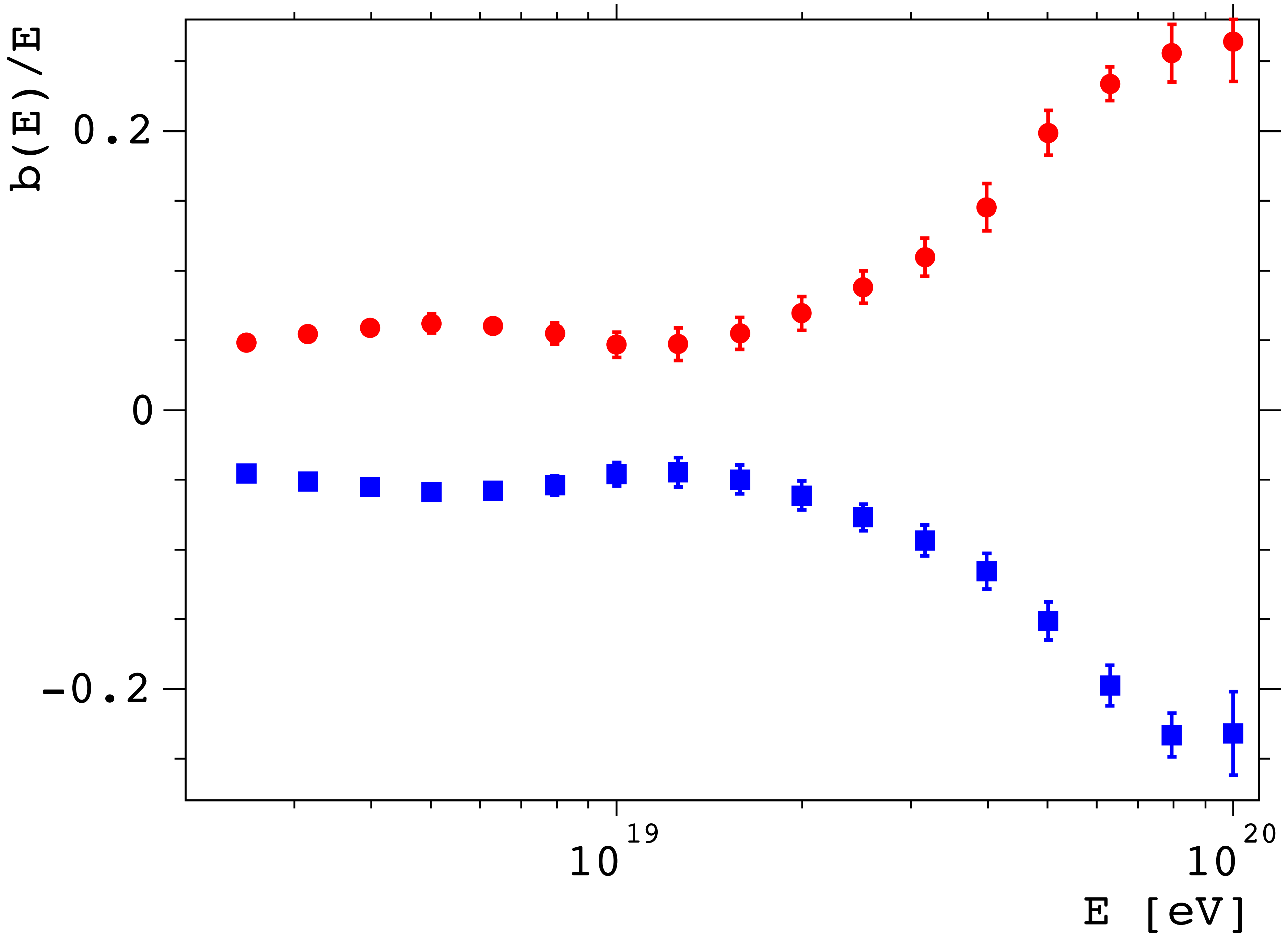
Bringing the spectra in agreement around the ankle

➡ Apply the same technique to the whole f.o.v. spectra (no need of the $1/\omega$ way in the energy range)

broken power law suppression



double broken power law suppression

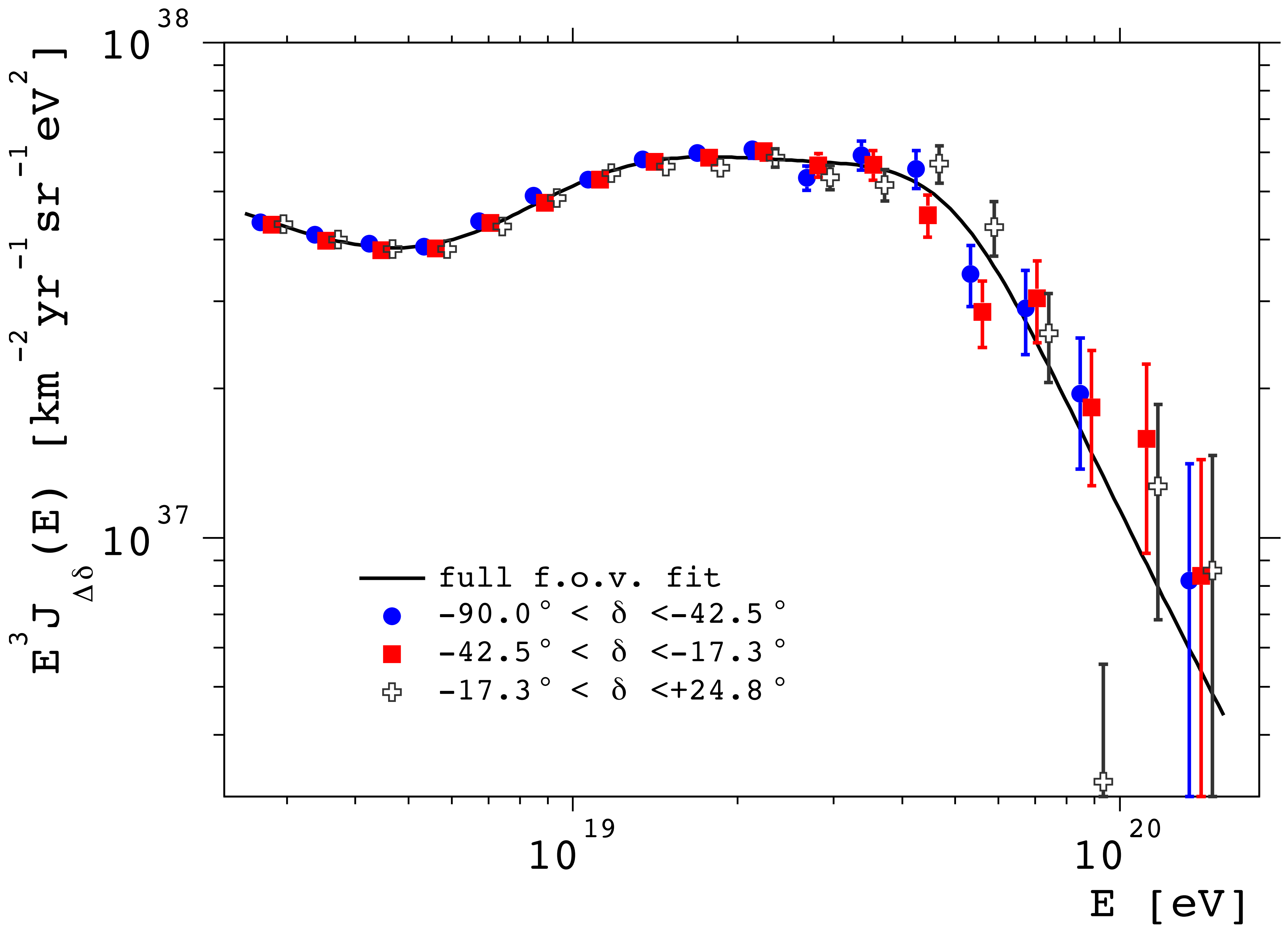


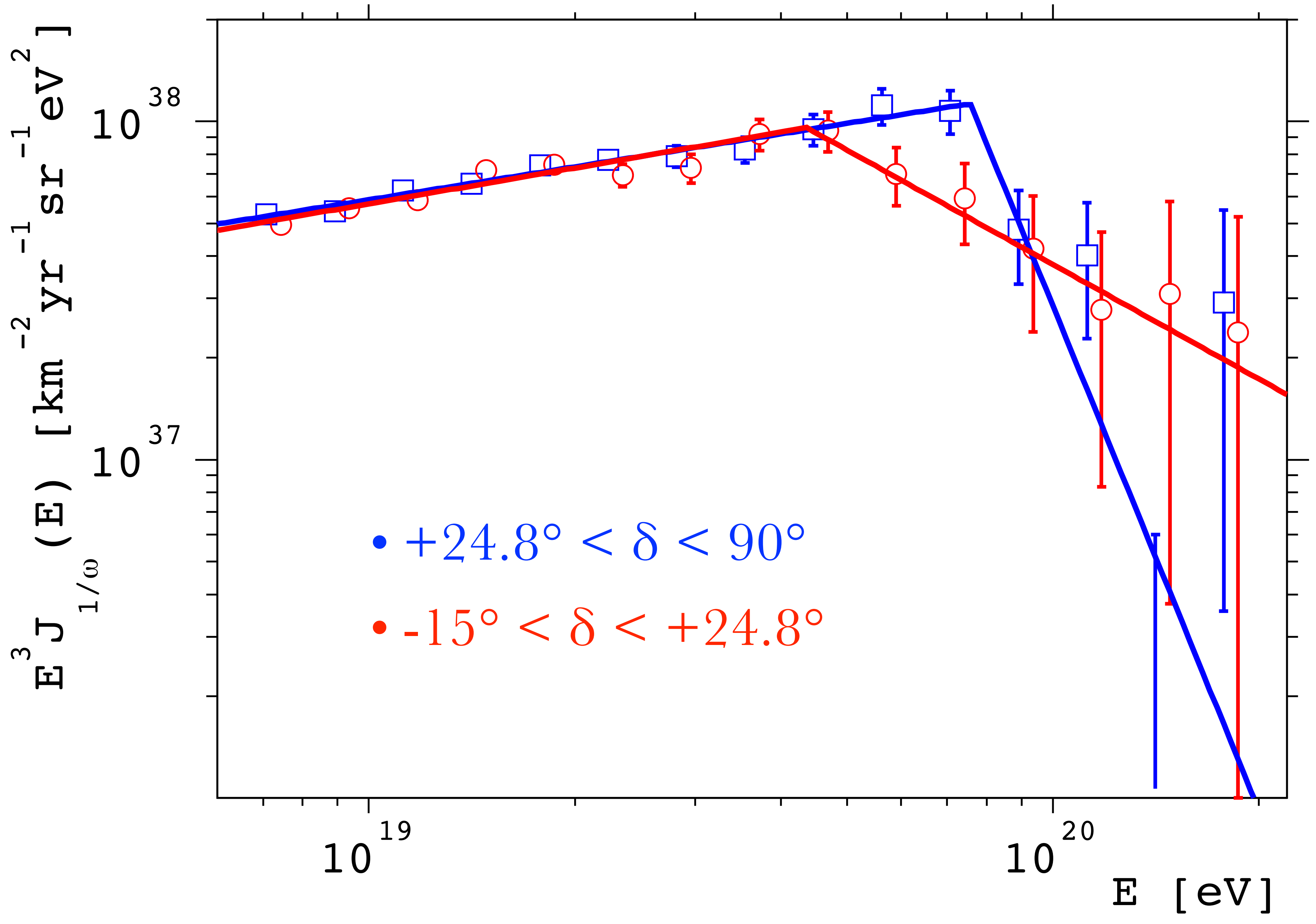
➡ Constant factor obtained, up to higher energies with the double broken power law

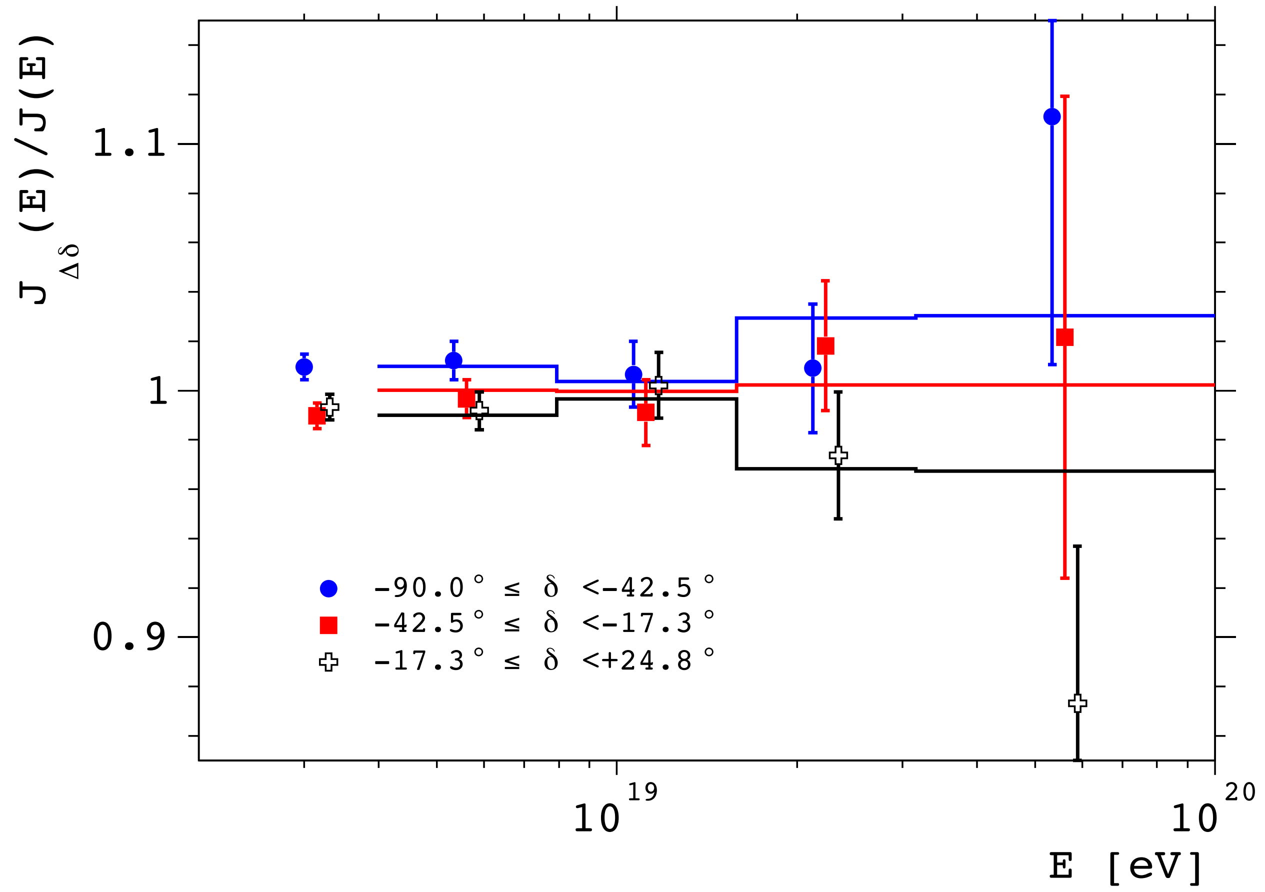
4. Declination dependences

- Searches for dependences in TA and Auger
- Northernmost vs Southernmost spectra

Searches for declination dependences in TA and Auger

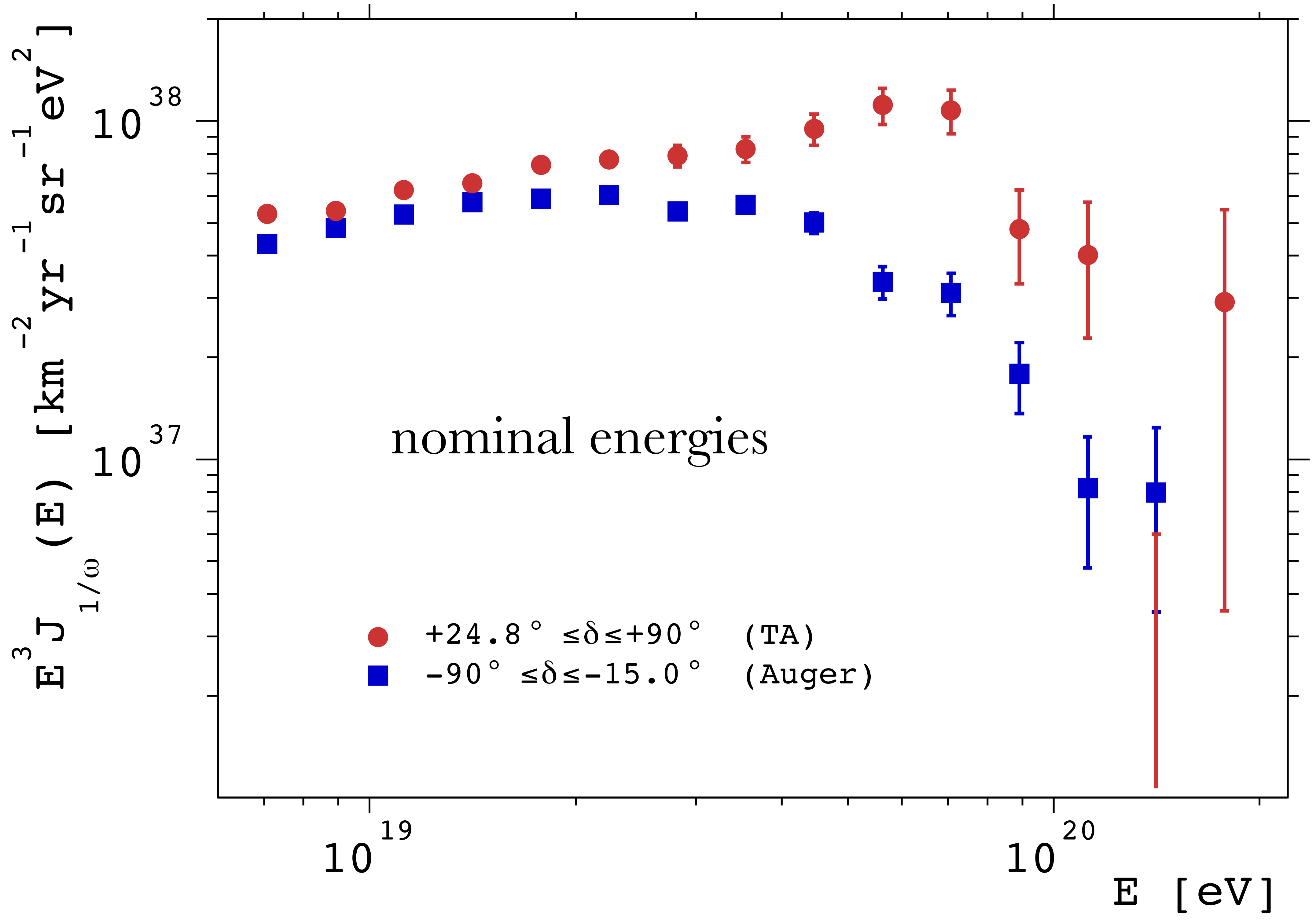


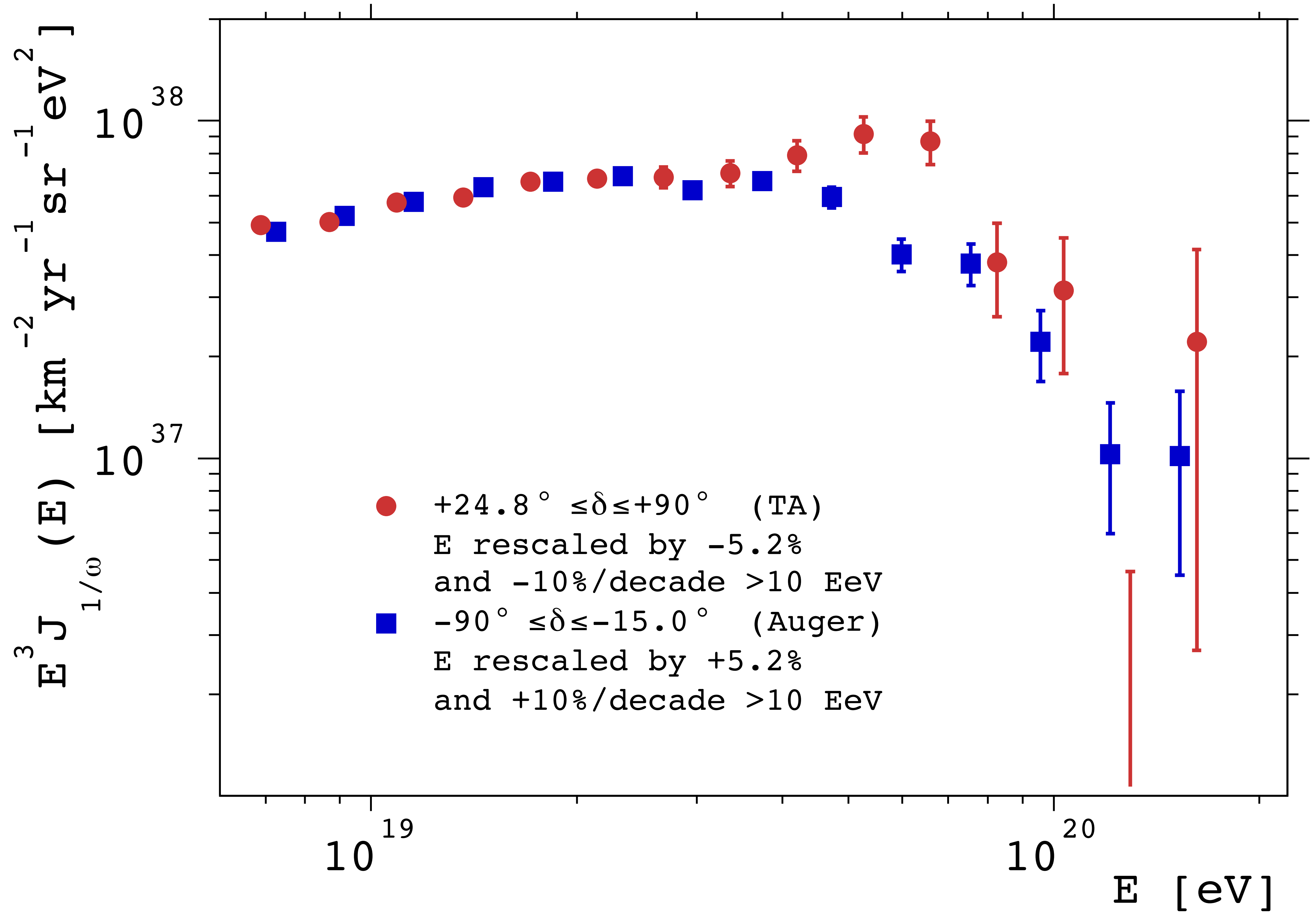




- Auger: Only a trend for a slightly larger intensity in the South (consistent with dipole expectations)
- TA: Differences in the suppression energy, with an excess of intensity in the Northernmost sky

North vs South excluding the common declination band





➡ Excess of intensity in the Northernmost declinations around the suppression energy

(no sign of declination-dependent systematic effect on the energy estimate from E/W cross-checks)

Conclusions

- Good agreement from the 2nd knee to the ankle energy ranges modulo a rescaling factor of the energy scale (invisible energy corrections)
- Global rescaling of energies (FY) from the ankle to ~10 EeV
- Non-linearity above 10 EeV captured in the overlapping declination range
- A single non-linearity prefers a double broken power law suppression
- Sources of non-linearity not identified
- Further studies of the systematic uncertainties in TA and Auger:
    - Auger detectors at the TA site for understanding the SD response
    - Reduction of statistical uncertainties with the future TA x 4 expansion and continuous Auger data taking
    - Comparisons between scintillators – only SD fluxes between AugerPrime and TA